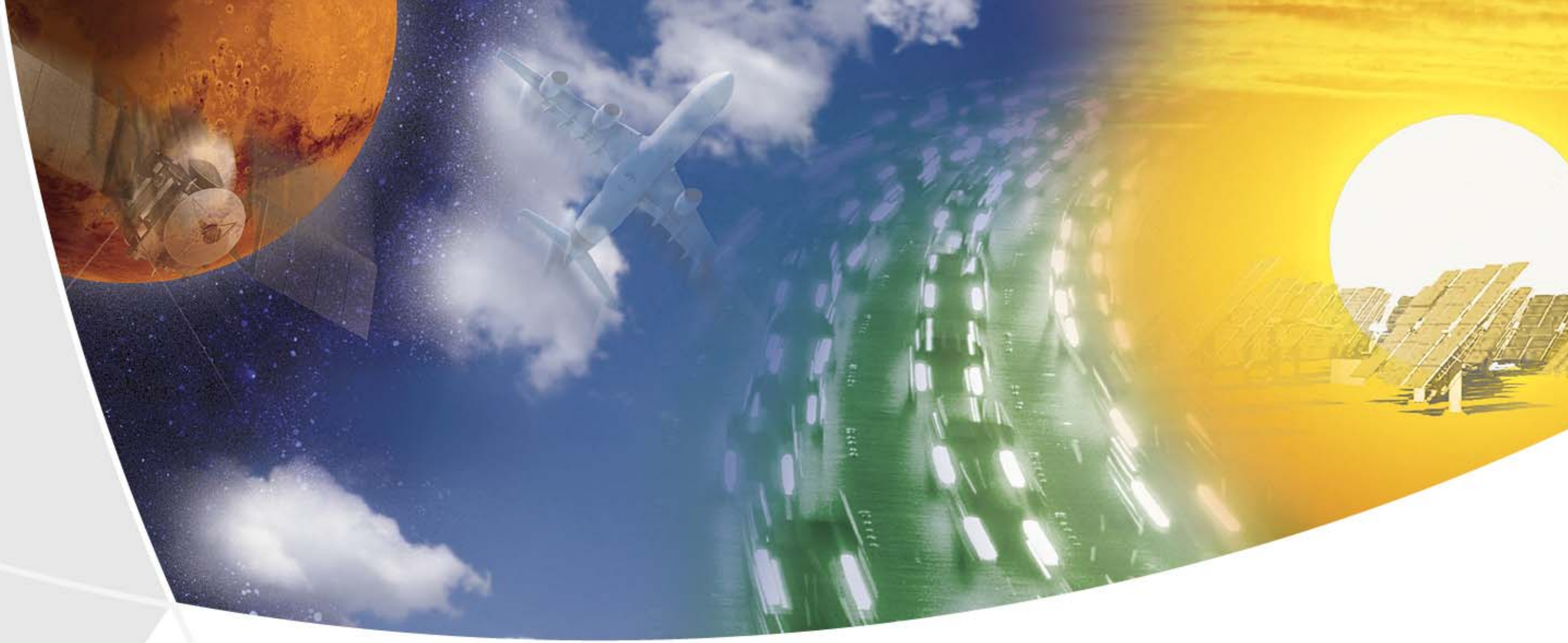

Ignition of Gaseous Methane/Oxygen Coaxial Mixtures

J. Sender, C. Pauli, M. Oschwald

DLR Lampoldshausen

Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

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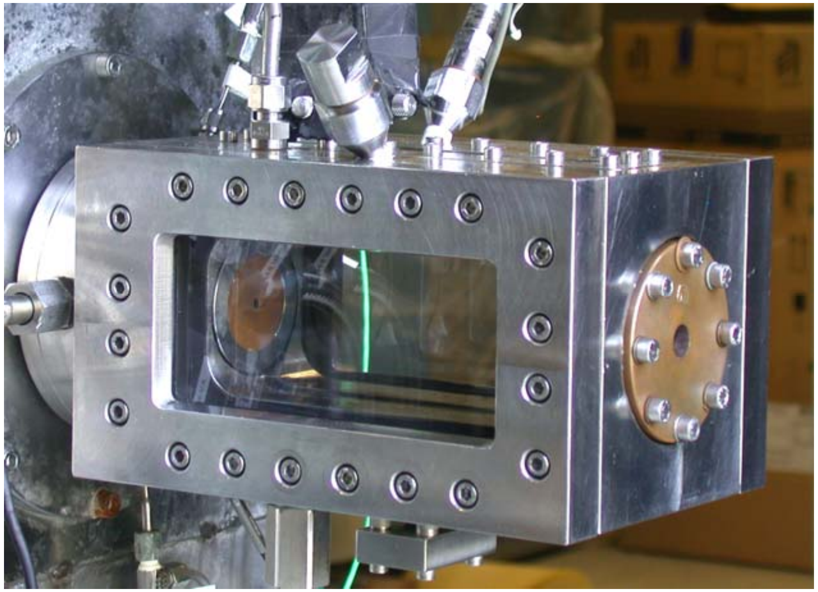
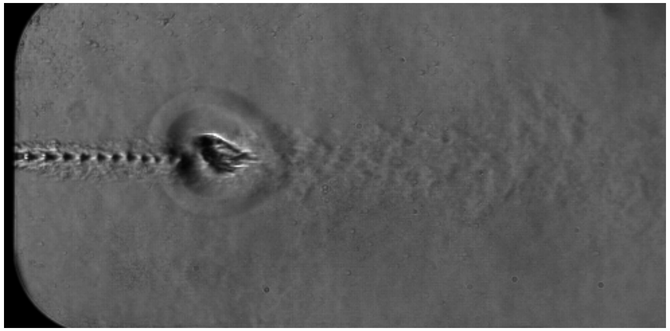


- Motivation
- Experimental setup & Test Conditions
- $CH_{4/}O_2$ Ignition phenomenology
- Mass flow rate effects
- Flame Stabilization
- Flame Anchoring - Influence of V & J ratios
- Conclusion

Motivation

- Ignition is still an issue for liquid propellant engines…reignition capabilities, etc.
- Goal : understand the ignition process to guarantee a reliable ignition
- Require: Focused experimental investigations on which to base specific CFD simulations

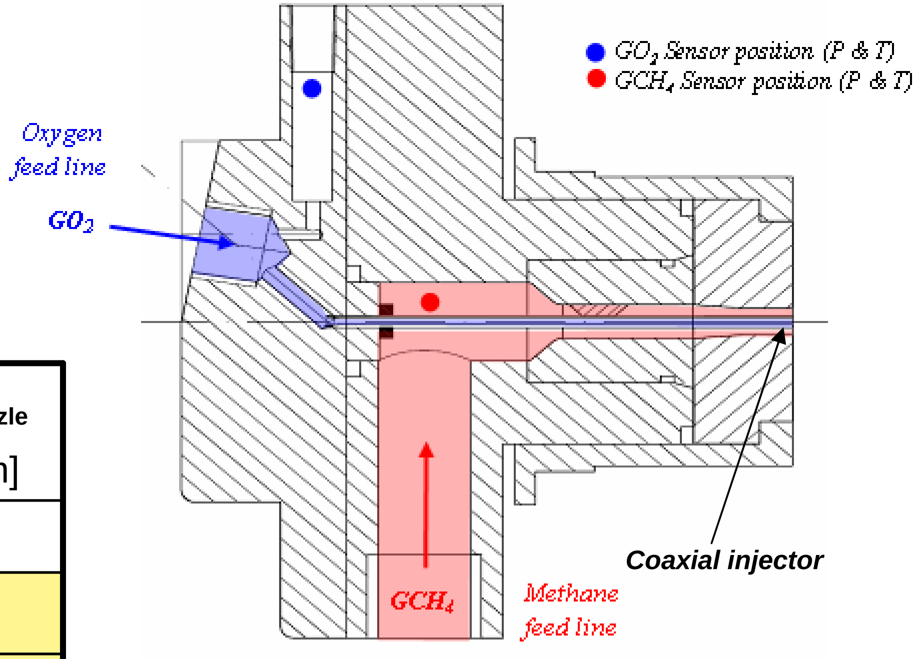


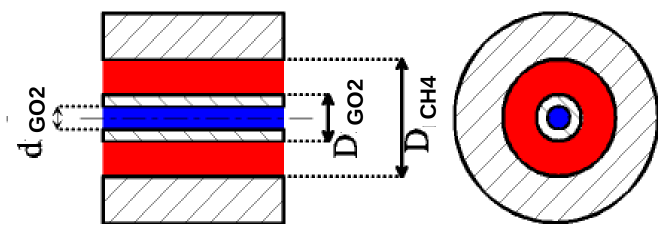
Experimental Setup (1)

Geometry

- Simple coaxial injector
- Four different injection configurations
- Test duration: 1 second

Test case	d_{GO2} [mm]	D_{GO2} [mm]	D_{CH4} [mm]	D_{nozzle} [mm]
Case A	1.6	2.4	4.0	6
Case B	2.5	3.3	4.3	6
Case C1	2.5	3.3	3.6	6
Case C2	2.5	3.3	3.6	4
Case D	2.5	3.3	4.0	6



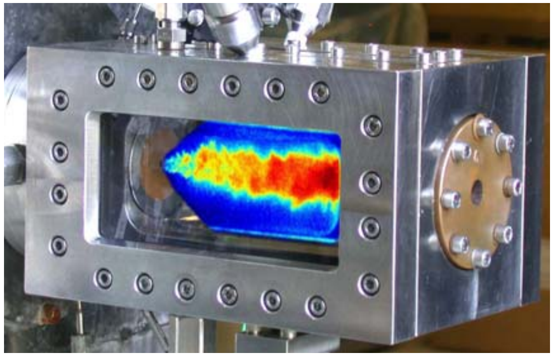


Experimental Setup (2)

Injection conditions

Test case	Chamber Pressure P_c [bar]	Total mass flow m_{tot} [g/s]	Mixture ratio ROF [-]	Methane velocity V_{CH4} [m/s]	Oxygen velocity V_{GO2} [m/s]	J [-]	V_{ratio} [-]
Case A	1.5	3.1	3.4	101	304	**0.02**	**0.33**
Case B	1.5 to 3.6	3.1 to 5.9	3.4	126	228	**0.13**	**0.54**
Case C1	2.3	4.6	3.4	412	239	**1.53**	**1.72**
Case C2	2.3	2.1	3.4	221	127	**1.56**	**1.74**
Case D	2.3	4.6	3.3	185	229	**0.30**	**0.81**

- *Momentum flux ratio J*: $J = \dfrac{\rho_{CH_4} u_{CH_4}^2}{\rho_{GO2} u_{GO2}^2}$
- *Mixture ratio ROF:* $r_{of} = \dfrac{\dot{m}_{GO\,2}}{\dot{m}_{CH\,4}}$
- *Velocity ratio :* $V_{ratio} = \dfrac{v_{CH\,4}}{v_{GO2}}$

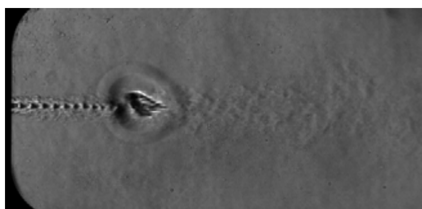


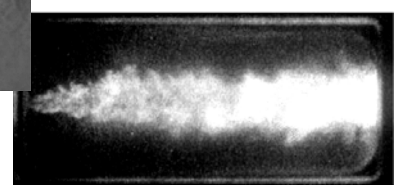
More than 100 tests performed

Experimental Setup (3)

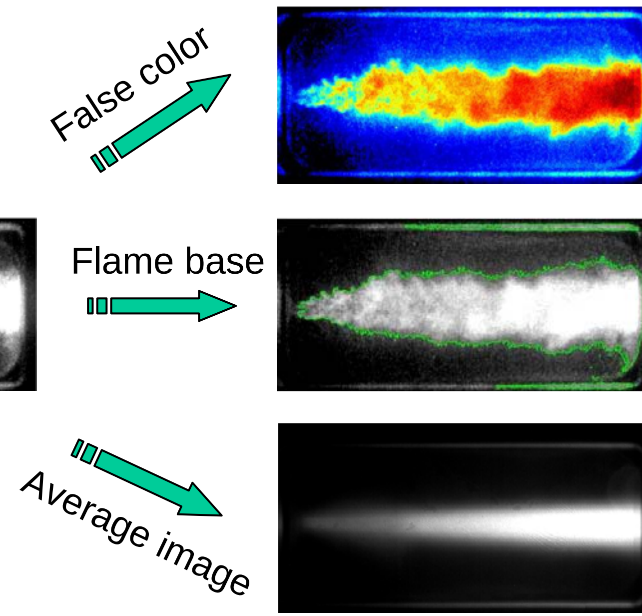
- **Laser Ignition**
  - Energy release in a specific volume by a focused laser beam
  - Less representative than with an igniter, but:
    - Results in a well localized plasma (with high temperatures ~ 106 K) → Position of initial flame kernel precisely known
    - Exact control of the ignition time to notably trigger the optical set up (Precision: +/- 10 µs)

Laser Type	Freq. doubled Nd:YAG
Wavelength	532 nm
Pulse Length	10 ns
Pulse Energy	95 mJ





Raw Image



- **Optical Diagnostics**
  - Visualization of transient flow and flame
    - **Schlieren** (Fastcam Photron High Speed CCD Camera Ultima 1024)
    - **OH Emission** Visualization (Fastcam Photron High Speed CCD Camera Intensified I2)

General Ignition Behaviour

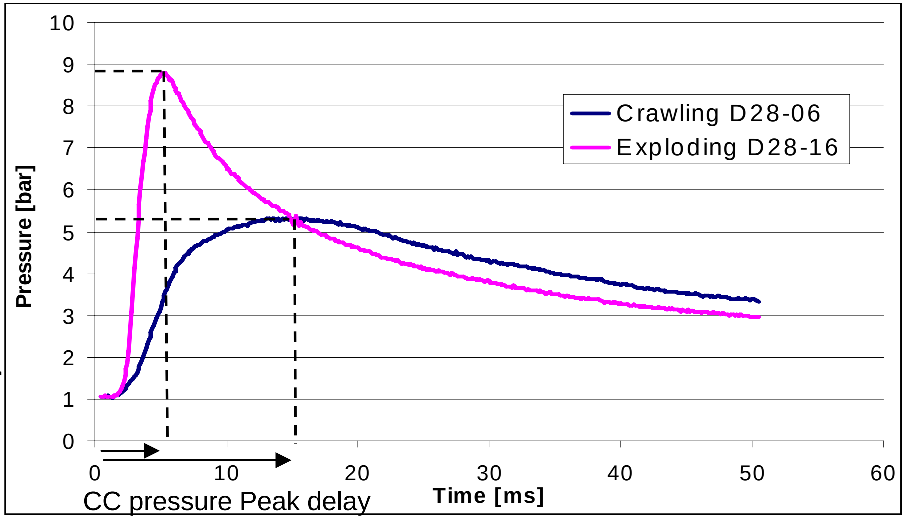
- Two ignition types found for every configuration:

- Crawling case, smooth ignition :
  - Low OH emission
  - Flame crawling to the injector
  - Once anchored: the flame develops
  - Smooth pressure build-up with max pressure of 5.3 bar at 15 ms

- Exploding case, hard ignition:
  - High OH emission
  - Sudden consumption of all propellants inside the chamber
  - Blow down of the flame
  - Re-ignition at the injector
  - High and fast pressure peak: 8.8 bar at 5.5 ms

Crawling (smooth ign.)

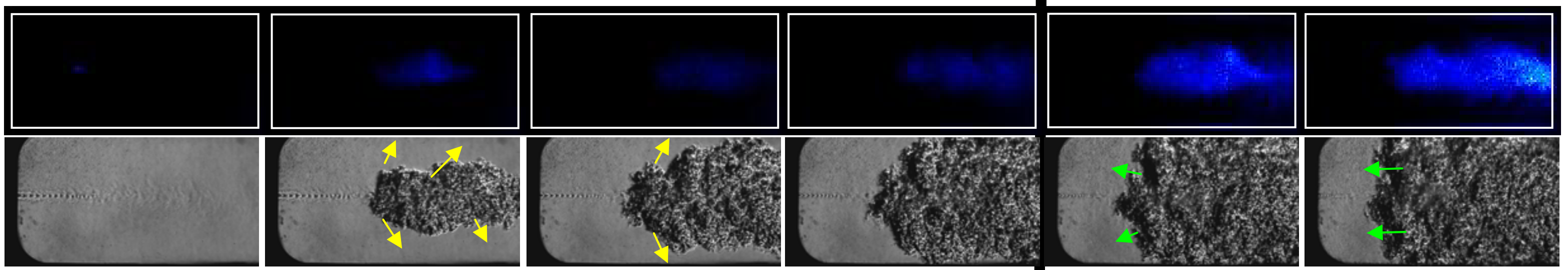
Exploding (hard ign.)



Crawling Case

A21-12
OH images
deltat=0.48 ms

Schlieren
deltat=0.5ms

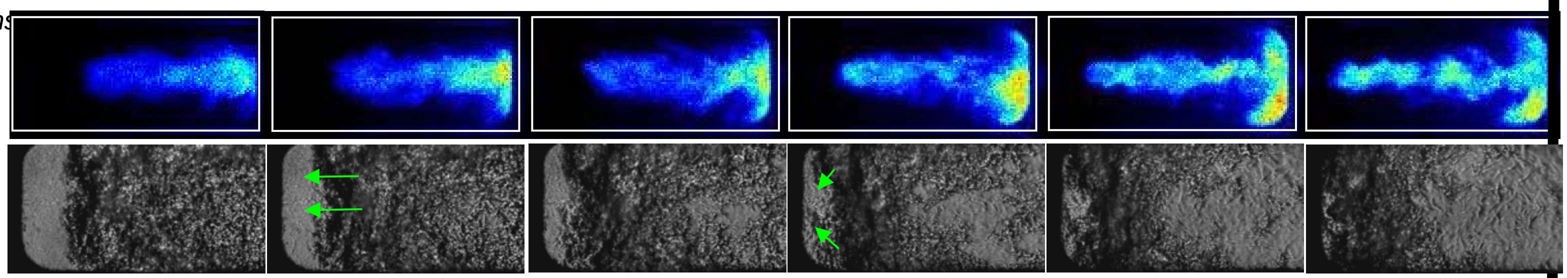


Phase 1 ***2***

Phase 1: Move Downstream Phase: 0 ms -> ~1.5 ms
Flame kernel moves downstream (but flow modified in the whole chamber)

t = 2.88 -> 5.28 ms

t =3.0 -> 5.5 ms

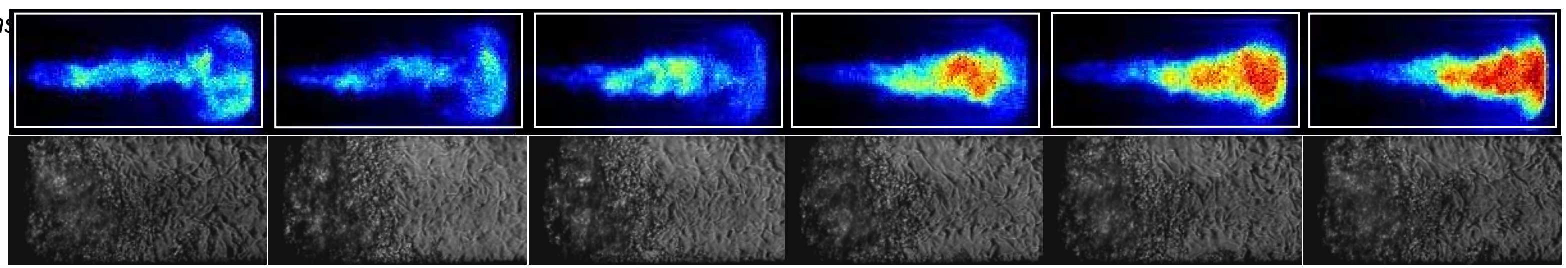


Phase 2 ***3***

Phase 2: Expansion phase: ~ 1.5 ms -> ~ 5.5 ms
Flame develops in intensity and moves upstream to anchor the injector

t = 5.76 -> 8.16 ms

t = 6.0 -> 8.5 ms

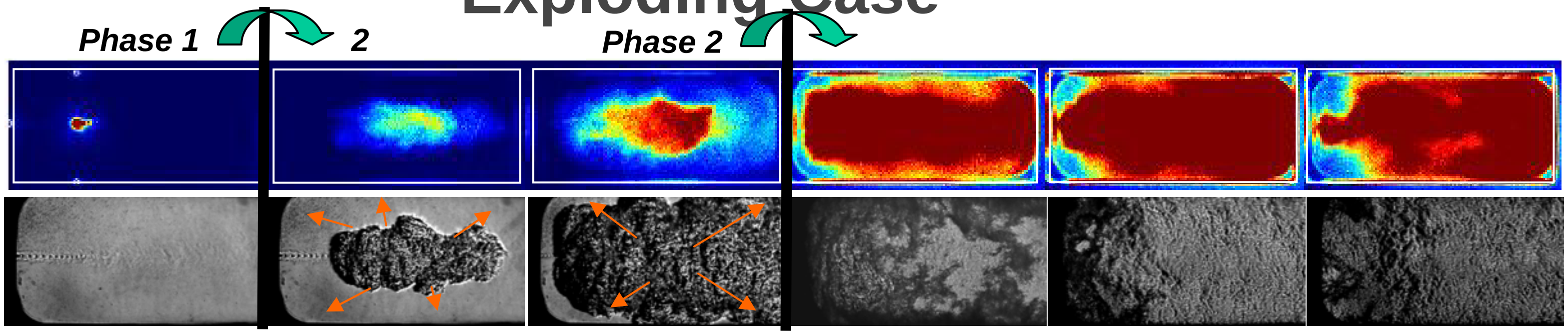


Phase 3: Flame development phase: ~ 5.5 ms -> steady
Flame is anchored to the injector lips and is develops up to the steady combustion (lifted flame or anchored)

Exploding Case

A21-12
OH images
deltat=0.48 ms

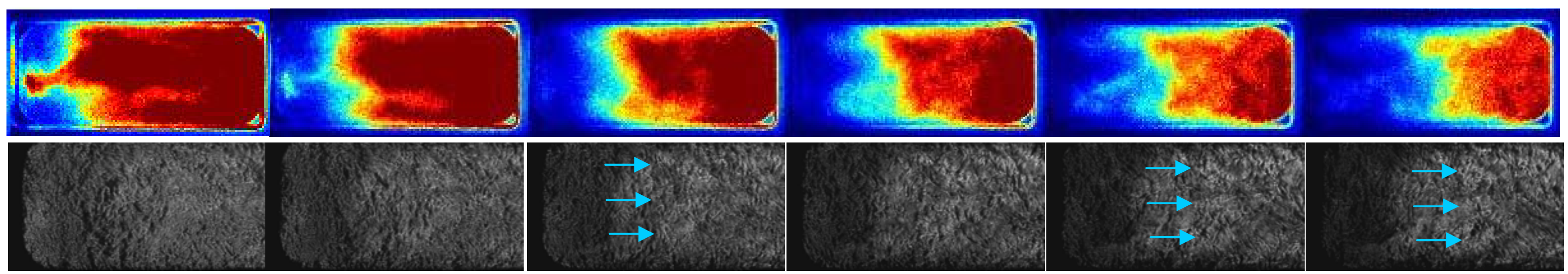
Schlieren
deltat=0.5ms



Phase 1 and 2: Blow down and Expansion phase : 0 ms -> ~ 3.5 ms
Sudden flame propagation consuming all the propellants accumulated in the chamber,

t = 2.88 -> 5.28 ms

t =3.0 -> 5.5 ms

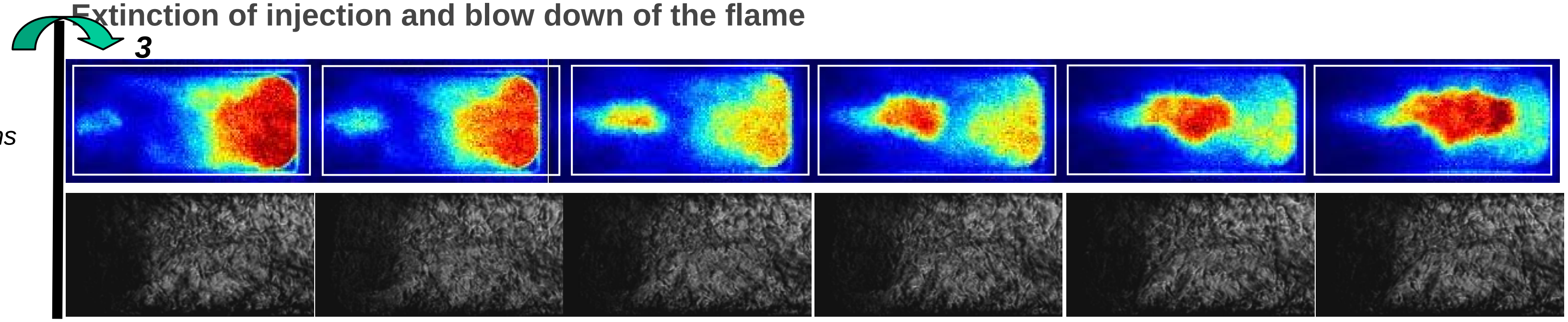


Blow out phase due to feed choke: ~3.5 ms -> 6.0 ms
Extinction of injection and blow down of the flame

Phase

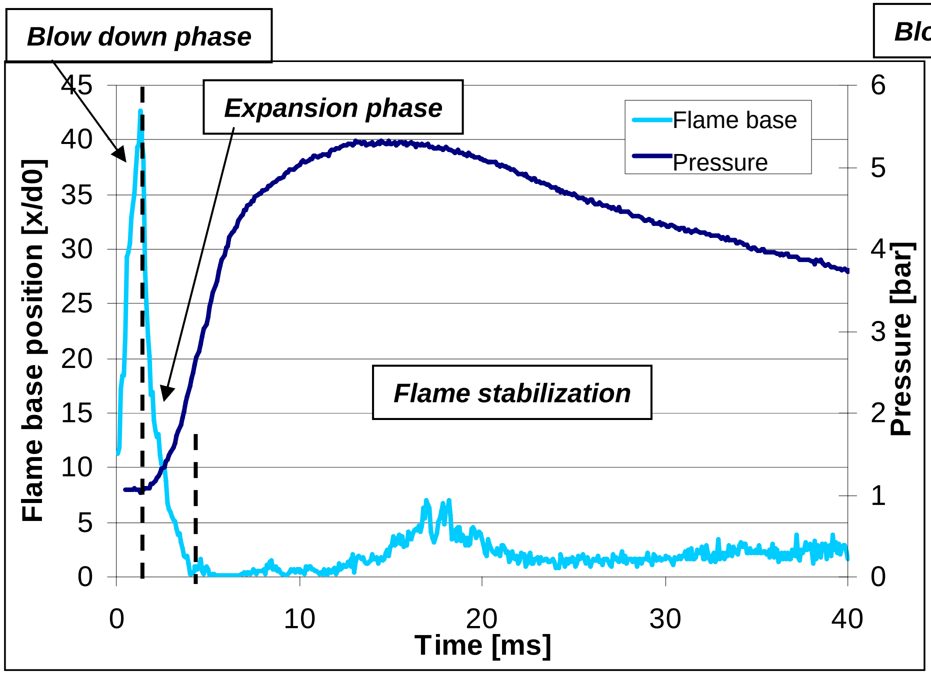
t = 5.76 -> 8.16 ms

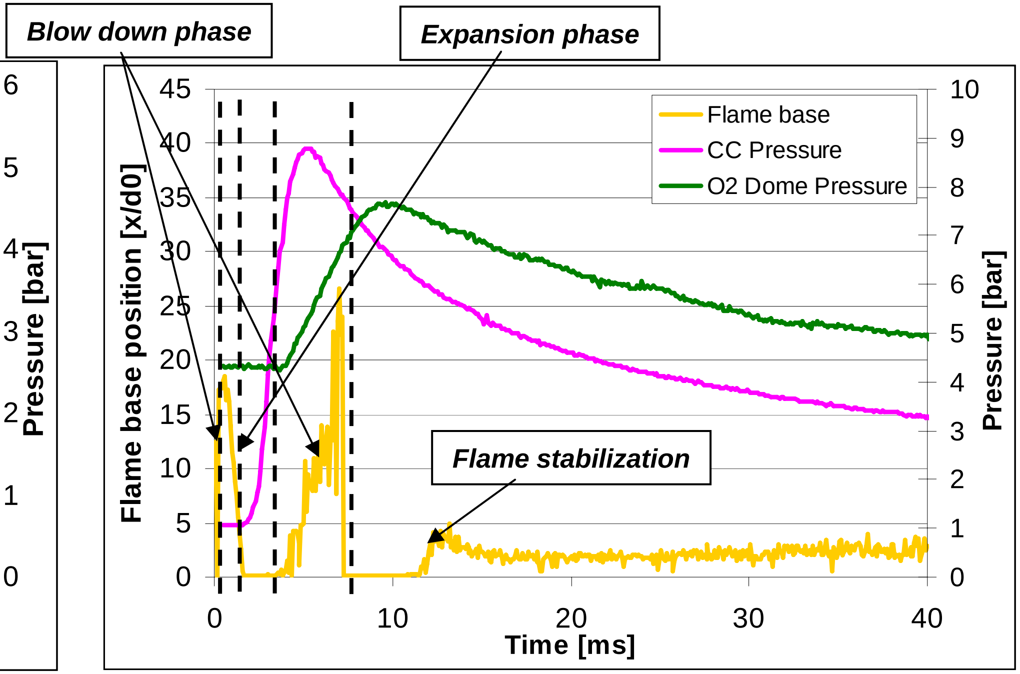
t = 6.0 -> 8.5 ms

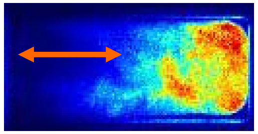


Phase 1, 2: Re-ignition phase with blow down: > 8.5 ms -> steady
Re-ignition of the flame at the injector lips, and flame developing

Flame base position



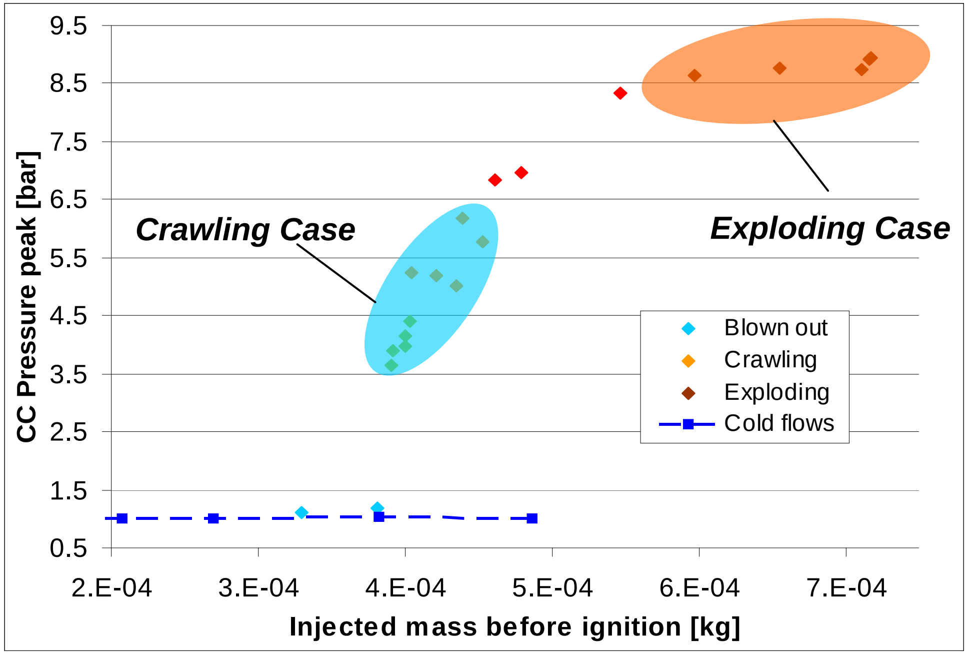




- Flame base position: Distance from the injector to the base of the flame
- Left: Flame anchoring without extinction of injection
- Right: Flame blown out because of the high CC pressure peak
  - Choking of oxygen injection
  - Re-ignition after pressure peak at the injector

Valve opening time

- Both type of ignition observed for every test cases
- Dependant of one parameter: the times of valve opening
- Earlier valves opening -> higher mass of reactants inside the chamber prior to ignition
  - Pressure peak higher
  - Change type of ignition -> crawling to exploding



- Injected mass = integration of the mass flow rate from the valve opening time to the ignition time

Influence of mass flow rate on ignition processes

(Test case C1/C2)

- Comparison with similar:
  - P_c = 2.2 bars
  - Same time of opening
    (same injected mass)
- Different mass flow rate:
  - Exit nozzle diameter: 6 & 4 mm
  - mass flow rate: 4.4 g/s & 2 g/s

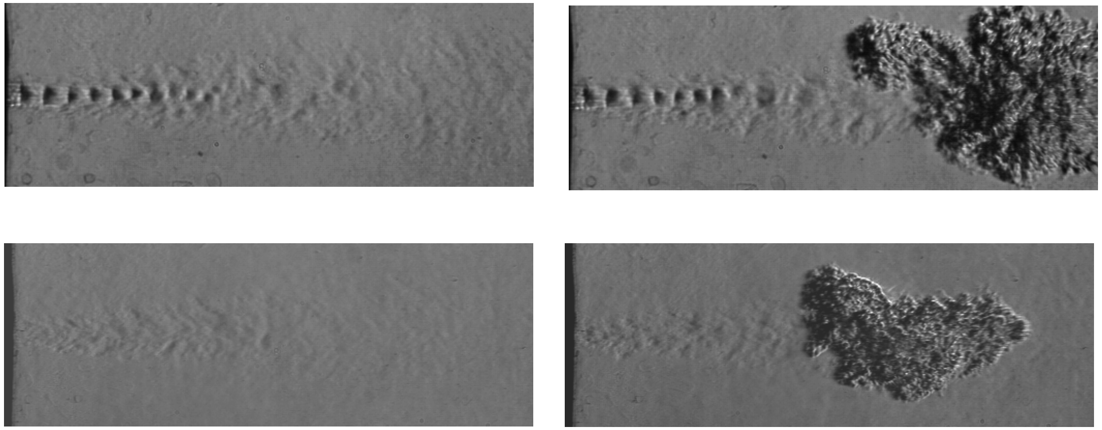
C125_11
High mass flow

C226_16
Low mass flow

t =0.0 ms | **t = 0.5 ms**

C125_11 High mass flow

C226_16 Low mass flow



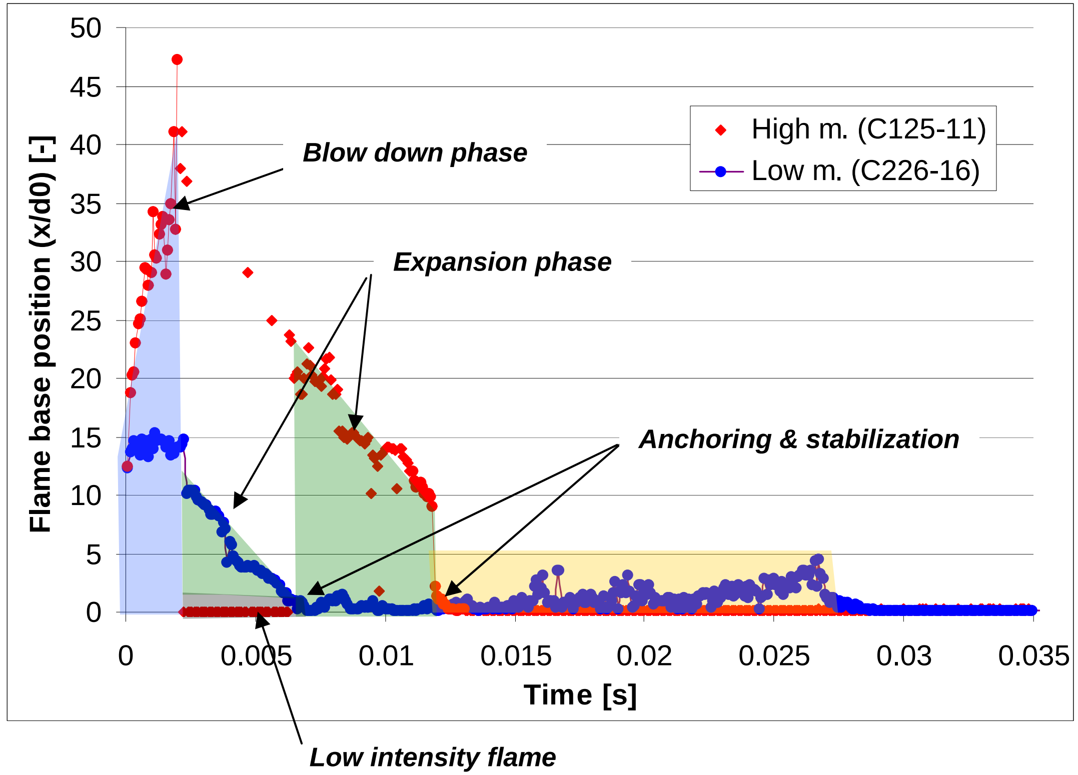
sonic jet at the ignition time

subsonic jet at the ignition time

Mass Flow Rate Influence on Ignition (Test cases C1/C2)

High mass flow case:

- Anchoring longer, due to high O_2-injection velocity
- Flame stabilization faster, presumably Injection condition are less sensitive to the variations of chamber pressure
- Low intens. flame: almost no OH emission visible
  - Front of gradient density moving upstream
  - Loc. of flame reoccurrence indicates loc. of low intens. Flame at the end of CC

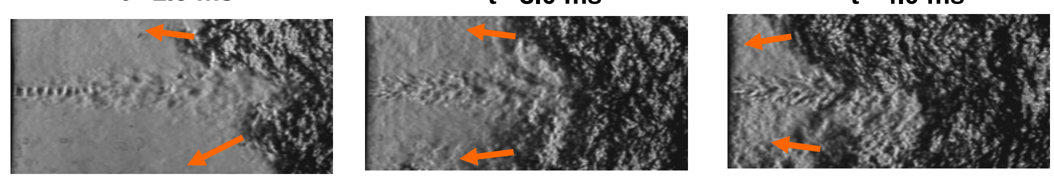


Three phases

- Blow down,
- Expansion &
- Stabilization found.

Depending on inj. cond. not every phase was equally temporal resolved.

t =1.5 ms t =3.0 ms t =4.0 ms



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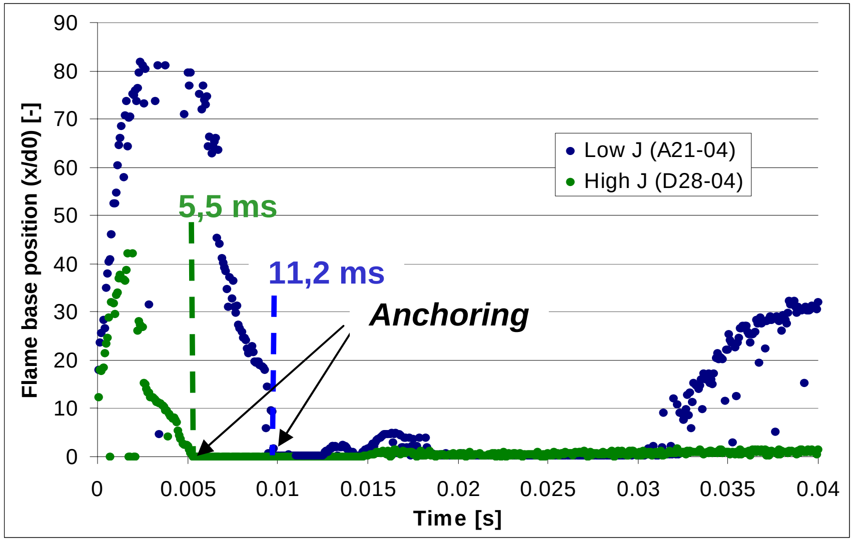
Influence of J number

- Comparison of injection processes with similar injected mass prior to ignition but with different J numbers:
  - J = 0.03 (case A) & 0.36 (case D)

A21_04
Low J number

D28_04
High J number

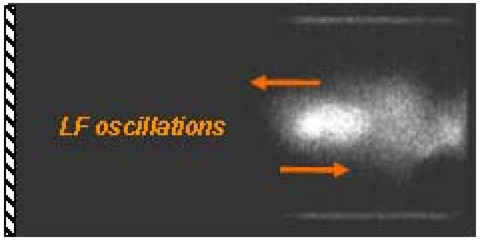


Flame Stabilization

CC Pressure Influence

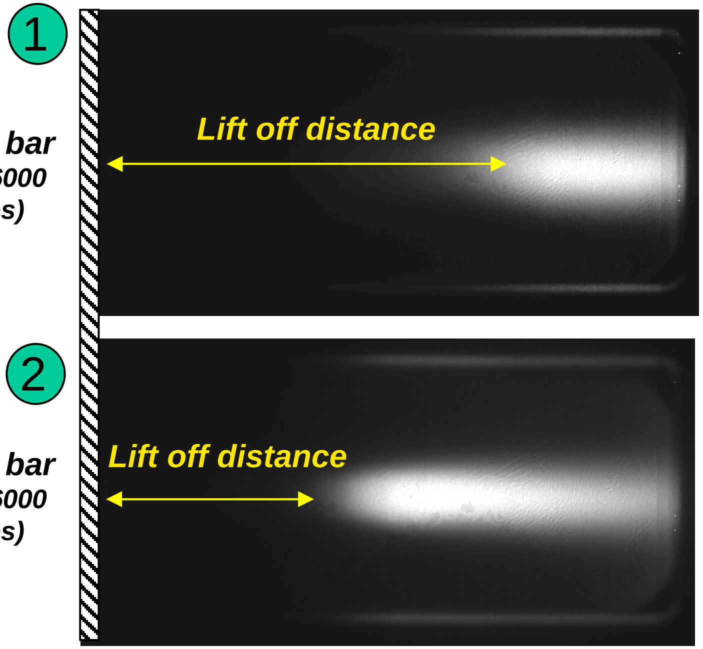
- Computation of the lift off distance on average image
- Higher chamber pressures lead to lower lift off distances:
  - *Pc = 1.5 bar* → $X_{Lift\ off} \sim 30\ d_0$
  - *Pc = 3.6 bar* → $X_{Lift\ off} \sim 15\ d_0$

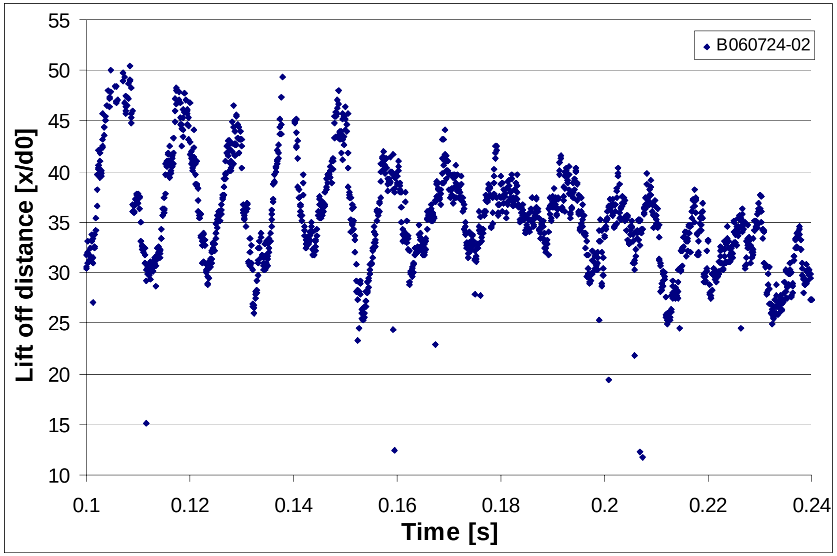
→ Higher stationary chamber pressure stabilize the flame



1 ***Pc=1.5 bar***
(500→6000 Images)

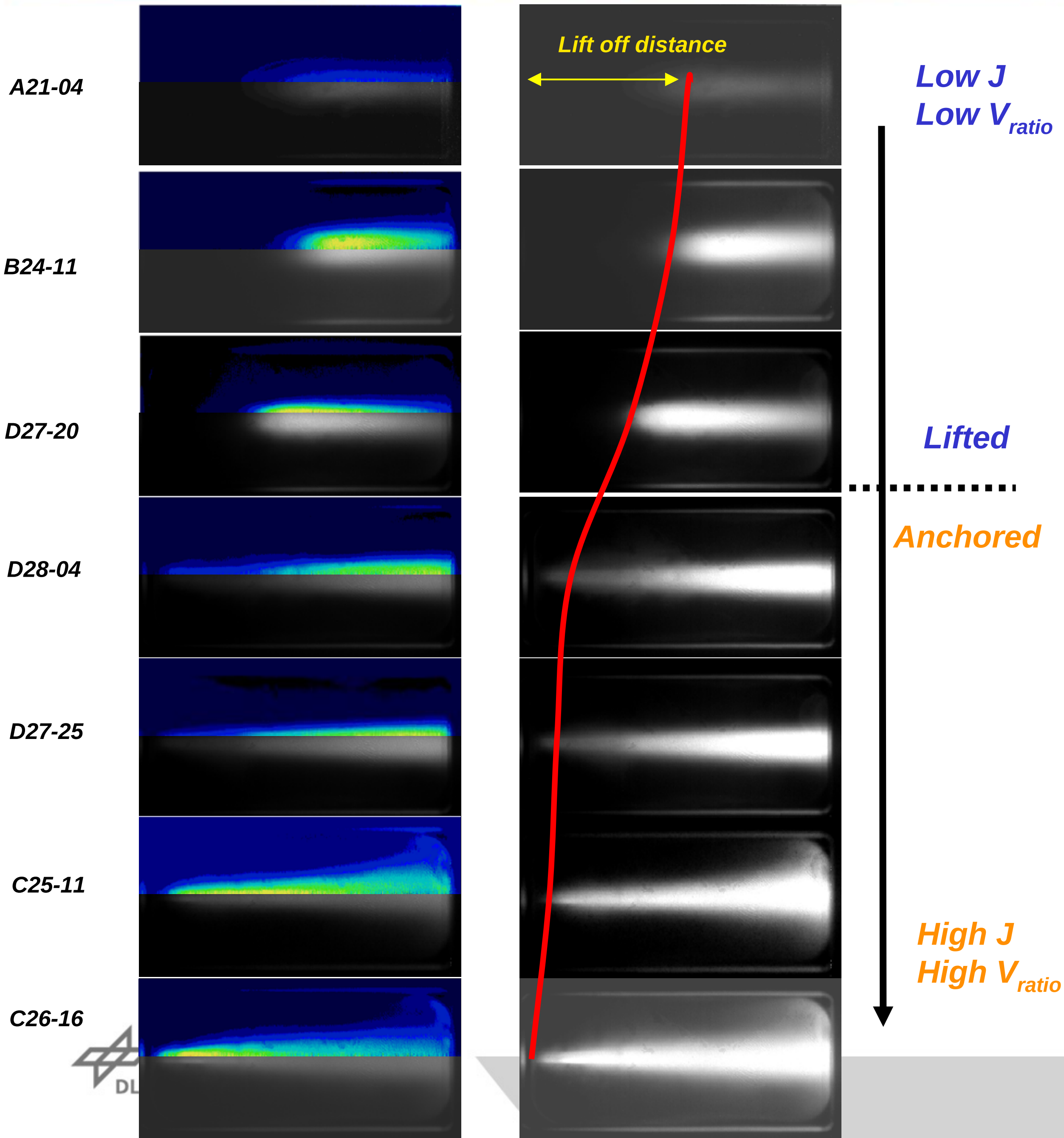
2 ***Pc=3.6 bar***
(500→6000 Images)





Flame Anchoring –

Influence of J & V ratios



Comparison of the average OH image during steady state combustion for every test

Test case	J [-]	Vratio [-]
A21-04	0.017	0.32
B24-11	0.134	0.54
D27-20	0.256	0.754
D28-04	0.292	0.802
D27-25	0.321	0.845
C1-25-11	1.72	1.52
C2-26-16	1.77	1.59

- Test case A, B: Lifted flame
- Test case C1, C2, D: Lifted flame & Anchored flames depending on the velocity ratio

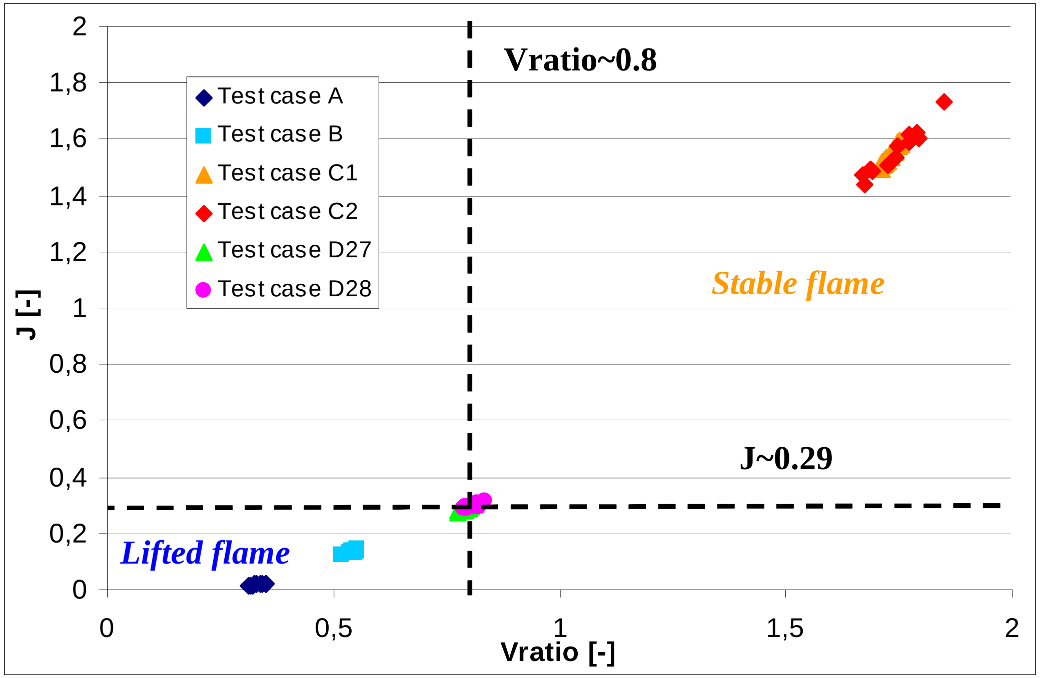
Flame Anchoring

Influence of the V ratio

- Critical value of velocity ratio to get a anchored or lifted flame:

  V_{ratio} > ~0.80 → ***Anchored Flame***

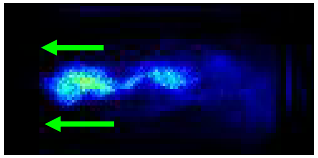
- With higher outer methane velocity, the local mixing inside the coaxial jet is better and the combustion enhanced, allowing thus the anchoring of the flame to the injector lips

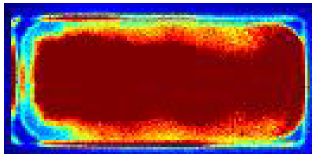


Conclusions

- **Reliable ignition of a gaseous CH_4/O_2 coaxial jet ensured**
  - **Influence of ignition time highlighted** (injected mass before ignition)
  - Three different ignitions phases (Blow down - expansion – stabilization)

Crawling ignition





Exploding ignition

- **Influence of J number highlighted**
  - High J number:

    Favors the flame anchoring because a of a more efficient local mixing of the propellants

- **Stabilization of the CH_4/O_2 flame to the injector lips ensured**
  - Chamber pressure increase favors the stabilization of the flame near the injector

Conclusions

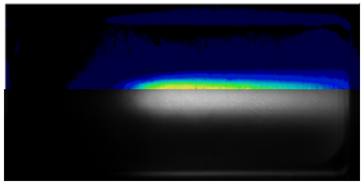
Stabilisation of the CH_4/O_2 flame to the injector lips ensured

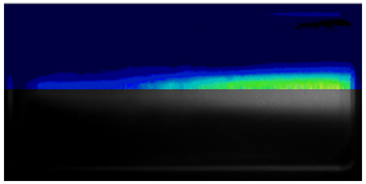
- Influence of the velocity ratio highlighted
  - For high V_{ratio} (> 0.8), the flame remains anchored

Provide qualitative and quantitative for further CFD Computations

- Precision in boundary conditions ensured in terms of pressure and mass flow rate (calibration + shocked sonic nozzles)
- High temporal and spatial resolution quantitative data (pressure sensors: 10 kHz, OH imaging: 12 500 Hz)
- Importance of modeling the dome injector in CFD computation

Lifted flame





Anchored flame